ENGINEERING
TECHNOLOGY

Boeing Aerospace Company

FLEXIBLE SPACECRAFT SIMULATOR

(860-7A202)

PROBLEM

- Verification of control algorithms for flexible spacecraft can be done only through simulation and test; these are necessary to understand control/structure interaction sufficiently to design robust controllers for future spacecraft.

OBJECTIVE

- To develop a low-cost facility which simulates the fundamental problem of C/SI.

- To provide accessibility for designs so that experience can be gained in applying various multivariable control design methods to an actual structure.

SIMULATOR HARDWARE

The simulator facility and test structure are shown in the figures. The structure consists of a rigid core to which six weighted arms are attached by short, flexible pins. This attachment provides rigidity in the vertical plane to support the weight of the arms, but flexibility in the horizontal plane. Thus, depending on tip weight, the arms display a first bending mode between 0.4 and 1.4 Hz. The structure rests on a plexiglass support disk which floats on a flat air-bearing table with no discernable friction. This gives the test structure three rigid-body modes (in the horizontal plane) and permits coupling of the bending modes to produce six lightly damped flexible modes with predicted frequencies below about 3 Hz. Symmetry of the arms results in several modes having nearly identical frequencies. The test structure weighs about 16 lbs; the short arms are about 30 in. in length, and the long arms are about 40 in. in length.

An available laboratory digital computer, an Apple-II+, is used as the controller and test data collection device. This machine turns out to be relatively slow (having a 1 MHz clock), so that careful coding was needed to get efficient calculation. Another reason for using this machine was the availability of an optical imaging device which has a direct digital interface with the computer through a plug-in board.

This device, called the Micron Eye*, is mounted above the center of the core and looks down on an X-shaped pattern. The image is transferred directly to the memory of the computer (in about 0.1 sec), where it is analyzed to determine translation and rotation of the core. Due to the pixel arrangement in the array, the field of view and quantization levels are different for the x-direction (i.e., the long direction of the pattern) and the y-direction.

In the current configuration, the x-axis field of view is about 7 in. and the resolution is 0.057 in., while the y-axis field of view is about 1.4 in. and the resolution is 0.022 in. The processing of the image produces an angle resolution of about 0.012 rad.

*Manufactured by Micron Technology, Inc., Boise, Idaho.

SIMULATOR HARDWARE (Contd)

To minimize cost, the test structure has been designed to require no on-board power or external connections. Control force actuation is accomplished by air jets which are fixed to the support table and directed toward fins attached to the support disk of the floated element. The jets are placed to permit about 4 in. of free motion, so that the forces generated on the fins will be equivalent to the reaction forces that would occur if the jets were mounted on the floated element. Air pressure for the jets is provided by a shop air supply through solenoid valves. To maintain subsonic flow in the system, a maximum pressure of about 15 psig is used, and the valve and nozzle orifices are 5/16 in. Tests show a jet thrust of about 0.2 lbs.

The valves are driven by a pulse-width, pulse-frequency (PWPF) modulator circuit which permits the use of a proportional control law with the on-off valves. The PWPF circuit has been designed to accept commands from a digital computer (through an 8-bit D/A converter) such that a command of 1-bit produces a minimum pulse-frequency of about one pulse per second. The maximum pulse frequency is about 30 pulses per second, which occurs at 50% modulation factor (i.e., 50% 'on' time).

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APPROACH

- Test facility is being constructed at U.W.

- Test element provides 3 rigid body and 6 flexible modes, all in the horizontal plane, with frequencies below about 2.5Hz.

- Control force actuation will be on/off air jets; sensing by optical displacement sensors.

- Loop closure will be accomplished using an Apple-II digital computer; control algorithms will be designed using the IAC, and MATRIX-X.
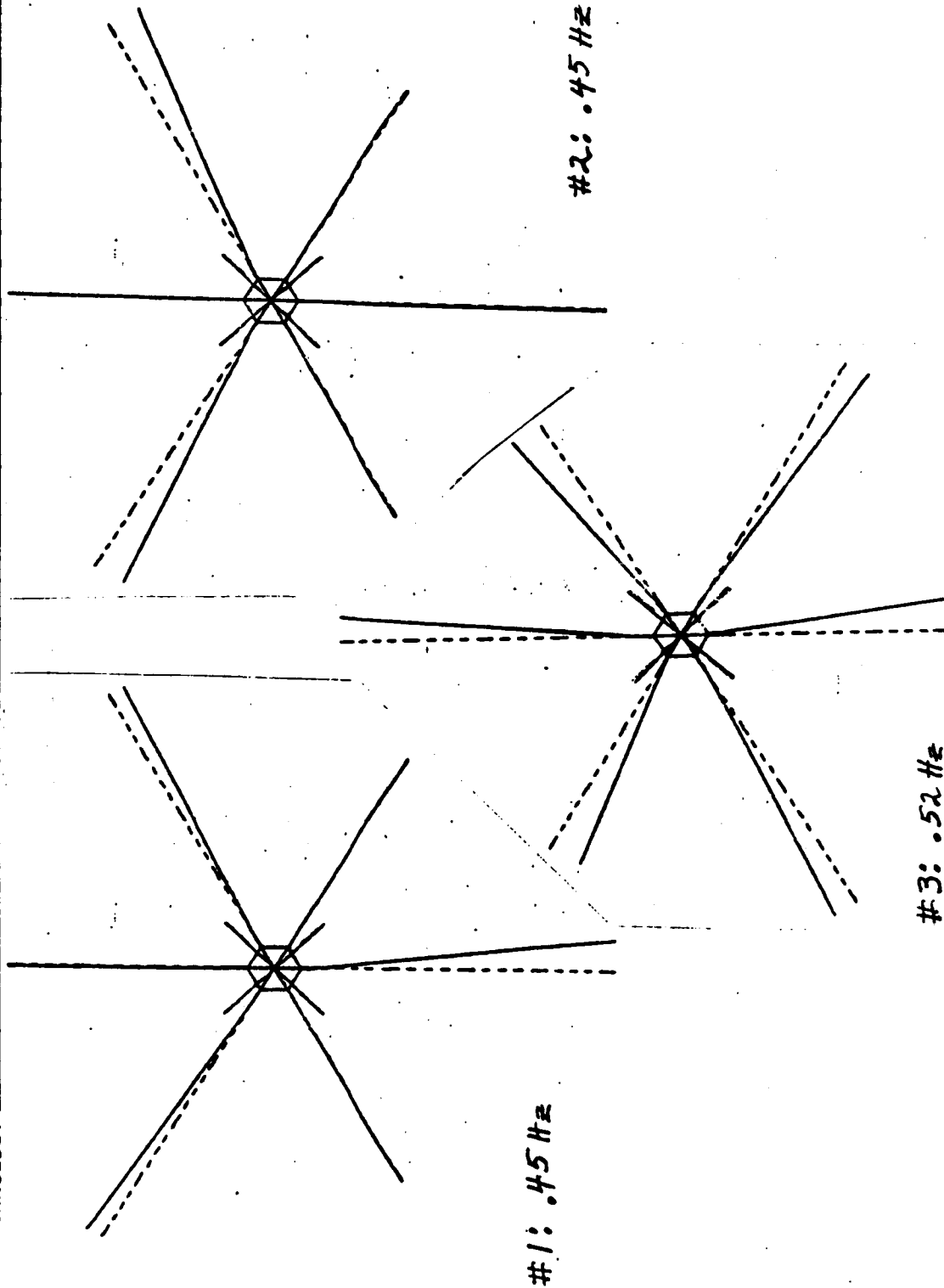
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STRUCTURAL ANALYSIS

A NASTRAN model of the test structure displays the six flexible mode frequencies and mode shapes. The three lowest frequency modes have shapes as shown. The first two involve translation of the core while the third is a pure rotation mode. The higher frequency modes have similar shapes but involve short arm motion.

With 0.2 kg weights on the arm tips, some tests were made by manually applying periodic inputs and timing the resulting oscillations. The results show modes at 0.40, 0.43, 0.54, 0.57, and 2.5 Hz.

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INITIAL CONTROL ALGORITHM TESTS

Following careful calibration and adjustment to minimize the effects of nonlinearities (e.g., quantization), a series of closed-loop tests have been conducted with a control law which treats the test structure as a rigid body. The x-, y-, and angle channels are assumed to be independent for this case. Since the sensor provdides only displacement measurements, rate information must be derived.

The design utilizes a 2nd-order observer and state feedback regulator on each channel. The low sample frequency prompts the use of a direct digital design. The control law software includes an initialization routine whereby the estimator and regulator pole locations in the z-plane can be input and the gains are calculated for the rigid body model.

INITIAL CONTROL ALGORITHM TESTS

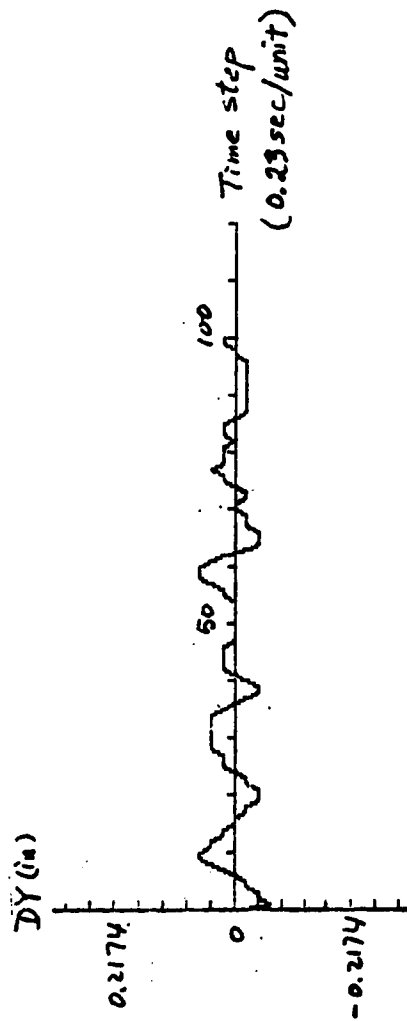### RIGID-BODY CONTROL LAW DESIGNS

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- x-, y-, and θ- channels are independent
- 2nd order observer and state feedback regulator are used on each channel
- Sample Interval: 0.23 sec
- Designed Closed-Loop Pole Locations:

		Z-plane	S-plane
Case 1:	reg.:	$0.57 \pm 0.30J$	$-1.9 \pm 2.1J$
	est.: x,y:	$0.50 \pm 0.30J$	$-2.3 \pm 2.35J$
	θ:	$0.41 \pm 0.32J$	$-2.8 \pm 2.9J$
Case 2:		Same as Case 1	
Case 3:	reg.:	$0.77 \pm 0.19J$	$-1.0 \pm 1.0J$
	est.:	Same as Case 1	

CASE 1:

This case involves fixing the arms to produce a rigid body. With the regulator and estimator poles as shown previously, the closed-loop response for the 100 samples (23 sec) is well-behaved. Note the control activity in θ; this appears to arise from angular quantization effects on the rate estimate.
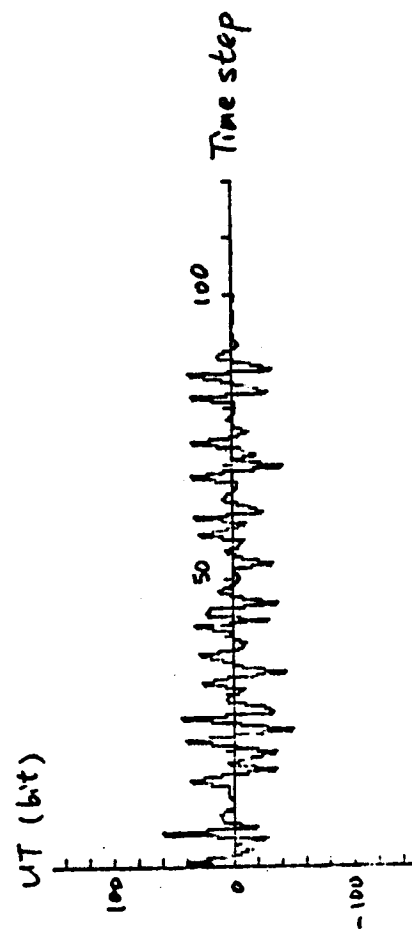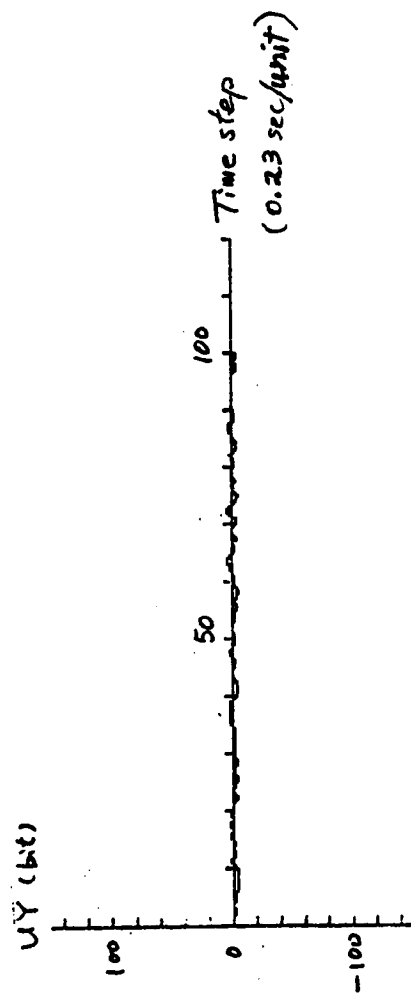
CASE 1: RIGID BODY DISPLACEMENT RESPONSE

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CASE 1: RIGID BODY CONTROL INPUTS

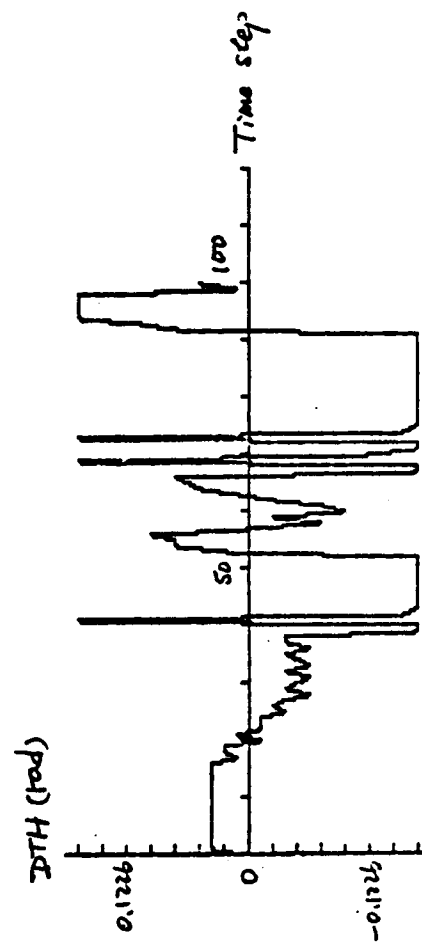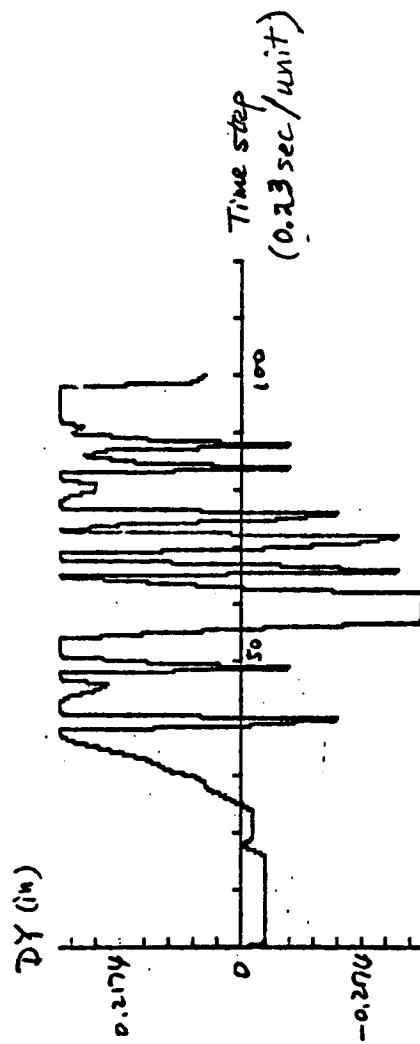UY (bit)

Time step
(0.23 sec/unit)

UT (bit)

Time step

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CASE 2:

This involves the same control gains as Case 1, but with the flexible modes present. The structure is held still for about 2 sec, then released (by turning the air-bearing floatation on). Both Y and θ diverge very quickly and the θ commands reach saturation levels (of 125 bits). When y-displacement reaches the limit of the sensor field of view, control is lost and the structure bounces between its stops.

This demonstrates an instability induced by interaction of the control bandwidth with the structural modes which are not included in the control law. Analysis is in progress to identify which modes are involved.
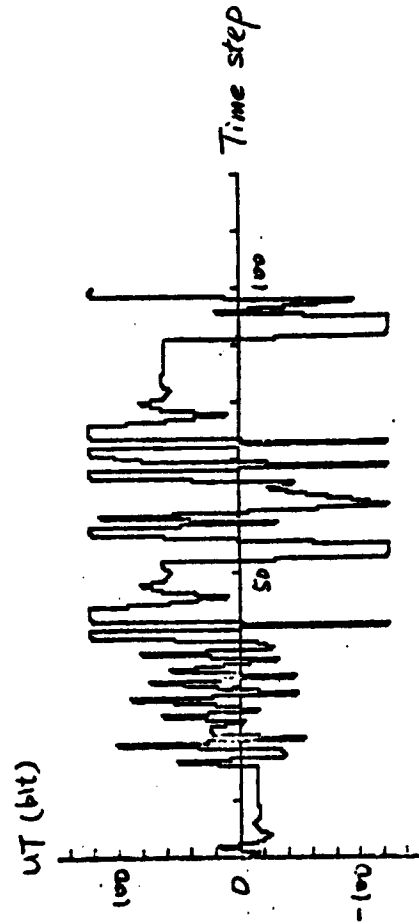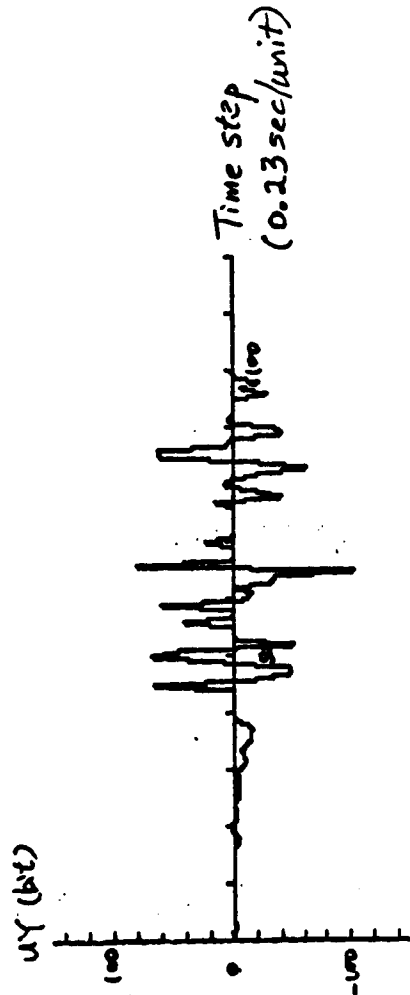
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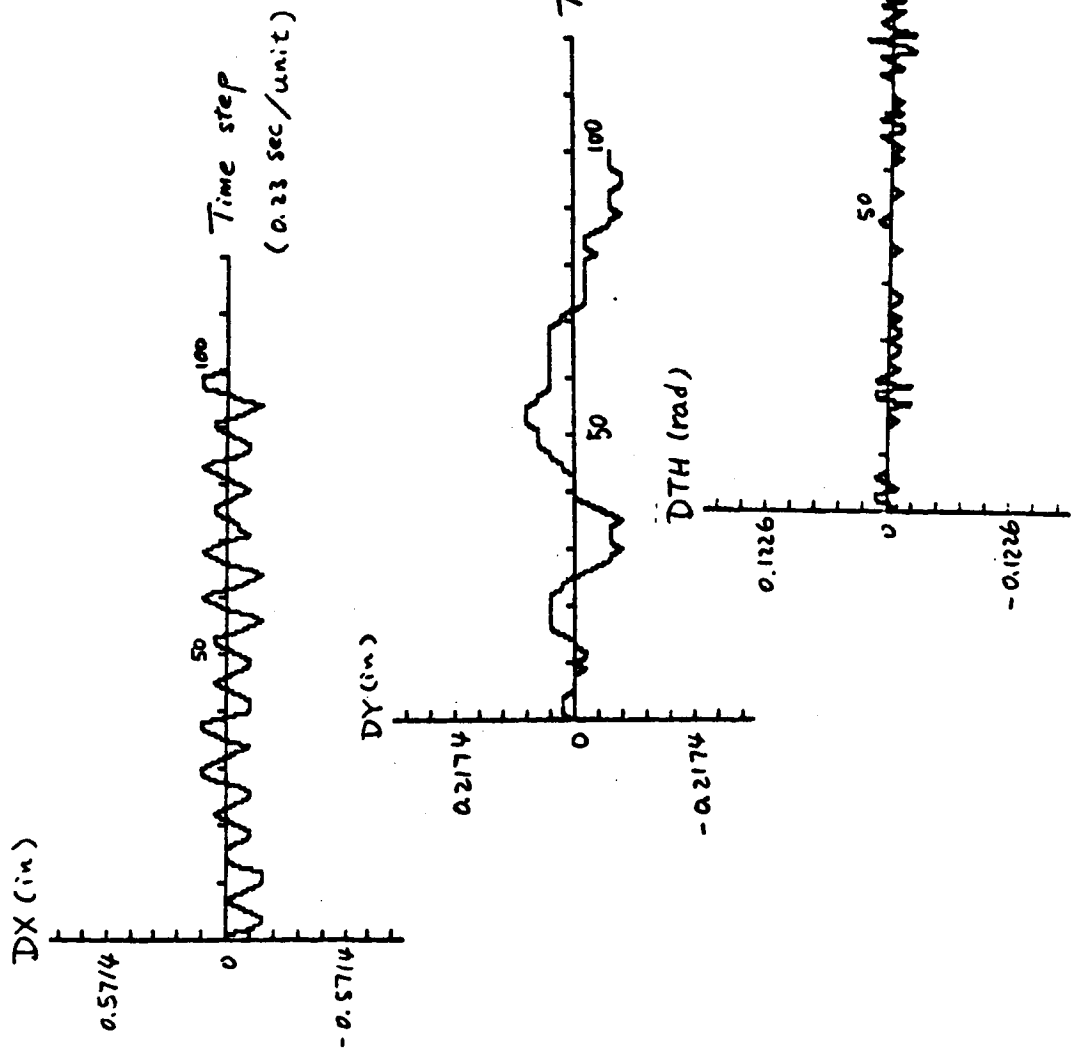TECHNOLOGY

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CASE 2: FLEXIBLE BODY CONTROL INPUTS

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CASE 3:

In this case, the flexible modes are present, but the regulator gain has been reduced. A lightly damped oscillation is observed in the x-displacement at about .58 Hz, but the system is stable with bounded control commands.

This demonstrates that narrowing the control bandwidth reduces interaction with the structural modes, thus restoring stability. The next step will be to include the flexible modes in the control law and again widen the control bandwidth to find the limit of stability.

CASE 3: FLEXIBLE BODY CONTROL INPUTS

CASE 3: FLEXIBLE BODY DISPLACEMENT RESPONSE

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UX (bit)

Time step
(0.23 sec/unit)

UY (bit)

Time step

UT (bit)

Time step